Ablation of Human Nail by Pulsed Lasers

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Background and Objective: **The hard and resistant structure of the nail plate forms a natural barrier that limits the penetration of topical drugs. To overcome this barrier, the use of pulsed laser systems has been suggested. The purpose of this study was to evaluate the effect of four laser systems on nail plate ablation rates, ablation efficiencies, and subsequent craters morphology.**
Study Design/Material and Methods: **Solid state Er:YAG (2.94 μm, 250 μs), a Ho:YSGG (2.08 μm, 250 μs), a XeC1 Excimer (308 nm, 15 ns), and a novel solid-state ultrashort pulse laser (1.05 μm, 350 fs) were used. Ablation rates, surface morphology, and extent of collateral damage were evaluated using light and electron microscopy.**
Results: **Best ablation efficiencies were demonstrated with the ultrashort pulsed laser (1 μm/mJ), whereas maximum material removal per pulse was obtained with the Er:YAG laser (80 μm/pulse). Scanning electron microscopy showed cracking damage with both Ho:YSGG and Er:YAG. XeC1 and the ultrashort pulse system left tissue surfaces free of cracks or thermal damage.**
Conclusion: **With its minimal acoustical and mechanical impact, high efficiency, and negligible collateral damage, the ultrashort pulse laser at 3 J/cm^2 was found to be the optimal laser system for nail ablation. Lasers Surg. Med. 21:186–192, 1997.**

Key words: lasers; hard tissue ablation; nail; laser-tissue interactions; laser-induced plasma

INTRODUCTION

A variety of laser systems have been found useful in the treatment of selected dermatoses of the nail unit [1]. Vascular lesions of the nail have been treated with the pulsed dye, tunable dye, copper vapor, argon, and carbon dioxide lasers. Pigmented lesions have been effectively treated with the Q-switched ruby, pulsed dye, tunable dye, copper vapor, and argon lasers. The carbon dioxide laser has been widely used in the clinical management of patients with a variety of benign and premalignant neoplasms and inflammatory processes of the nail.

Presently, there is no effective treatment for psoriatic nails. The mainstay of treatment involves the topical application of high-potency corticosteroids, which may be aided by occlusion with nonporous tape. Alternatively, local corticosteroid

Contract grant sponsor: NIH; Contract grant numbers: 5P41RR01192, IR29-AR41638-O1A1, and IR01AR42437-O1A1; Contract grant sponsor: Department of the Navy; Contract grant number: N00014-90-0029; Contract grant sponsor: U.S. Department of Energy; Contract grant number: DE-FG0391ER61227; Contract grant sponsor: U.S. Department of Energy, Lawrence Livermore National Laboratory; Contract grant number: W-7405-ENG-48.

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Received 30 October 1996.

injection into the nail matrix or bed may be used. However, the latter approach is obviously unpleasant to the patient and yields inconsistent results [2].

For treatment of onychomycosis, oral griseofulvin was previously the mainstay of drug therapy. However, recent studies have shown that terinafine is more effective [3,4].

Human nails have a wide range of unique physical properties and growth characteristics. The nail plate consists of differentiated "dead" keratinocytes containing a matrix of tightly packed keratin filaments, which lie in the flat plane of the nail surface at right angles to the direction of growth [5]. Unfortunately, the hard and resistant structure of the nail plate (although more permeable than the stratum corneum) provides a principal barrier that limits the penetration of topical drugs.

Mid-infrared [6] and excimer [7] lasers are new tools that can be used for the ablation and removal of cutaneous structures. For nail surgery, the ideal approach would be precise elimination of substrate to increase penetration of topically applied drugs, with minimal or no injury to adjacent residual tissues. Such an objective requires extremely high absorption of laser energy by protein or water, thereby confining the volume of photoexcitation to a thin layer of substrate at the irradiated surface. Although optical absorption is adequate at both the mid-infrared and excimer laser wavelengths to meet this objective, to date there has been no attempt to use these systems for the controlled removal of nail substrate. In addition, we incorporate preliminary results from a new 350 fs ultrashort pulse laser system which is now being investigated for a variety of applications in hard tissue surgery. This class of lasers has been shown in other studies [12] to have sufficiently high ablation rates while minimizing thermal or mechanical disruption of adjacent tissue. The potential advantages of the proposed removal of nail substrate in the clinical management of patients with psoriasis and onychomycosis are convincing: (1) increased penetration of topically applied drugs through the plate into the bed without removing the nail, (2) eliminate the need for systemic treatment and associated side effects, (3) treatment of mychomycosis in patients who cannot take terbinafine (i.e., allergy, immunosuppression, or multiple medications), and, (4) allow patients with only one or two diseased nails to receive treatment without having to use systemic medications for their limited involvement. In addition, by varying laser perforation size and number a new way of controlling drug delivery rates can be conceived.

TABLE 1. Comparison of Laser Parameters

Laser	Er: YAG	Ho: YSGG	XeCl	CPA
Pulse duration	250 μs	250 μs	15 ns	350 fs
Wavelength	2940 nm	2080 nm	308 nm	1053 nm
Fluence per pulse (J/cm^2)	10, 15, 20, 25	10, 15, 20, 25, 30	10, 15, 20, 25	1, 3
Pulse repetition rate (Hz)	4	4	4	10
Beam area	1 mm^2	1 mm^2	1 mm^2	0.4 mm^2

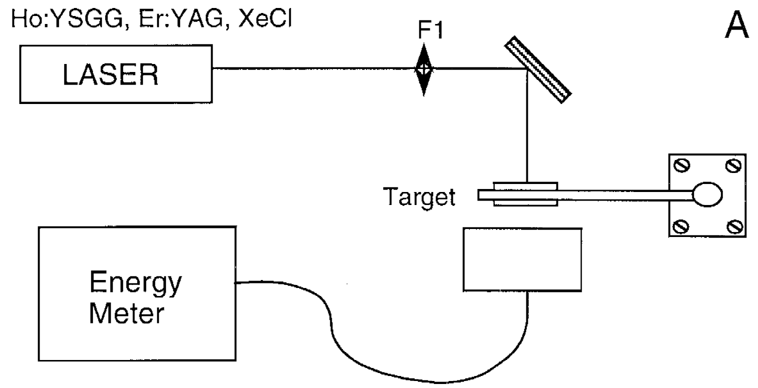
In this study, we have compared the effects of four laser systems on human nail plates. Using two mid-infrared (IR) lasers, a UV emitting excimer, and a near-IR ultrashort pulse system, we have investigated the effects of laser parameters (pulse duration, fluence, and wavelength) on controlled removal of nail substrate. In addition, by studying microstructural changes in the tissue below and around the ablation zones, we have attempted to determine if nail substrate can be removed without damage to adjacent residual tissues.

MATERIALS AND METHODS

Four laser systems were studied, including two commercially available solid state mid-infrared (IR) lasers, one ultraviolet (UV) Excimer system, and one Chirped Pulse Amplifier (CPA), variable pulse system (Table 1).

Operation of the IR and UV laser systems has been described previously in the literature [e.g. 9,10]. The CPA system utilized seed pulses of 100 fs from a Kerr-lens mode locked Ti: sapphire oscillator stretched to 1 ns in a four-pass, single-grating pulse stretcher. Amplification by nearly 10^9 to the 6 mJ range was achieved in the TEM_{00} stable cavity mode of a linear regenerative amplifier. Further amplification to the 60 mJ level was achieved in a Ti:sapphire ring regenerative amplifier, which supported a larger (2.3 mm) beam diameter and reduced nonlinear effects. The system was operated at 10 Hz; however, single pulses could be extracted for experiments (Fig. 1).

For all experiments, human cadaver nails were harvested and cleaned with a scalpel to remove any excess skin or nail bed so that only the nail plate was accessible to the laser. Nails were then placed in a sample holder adjusted to main-



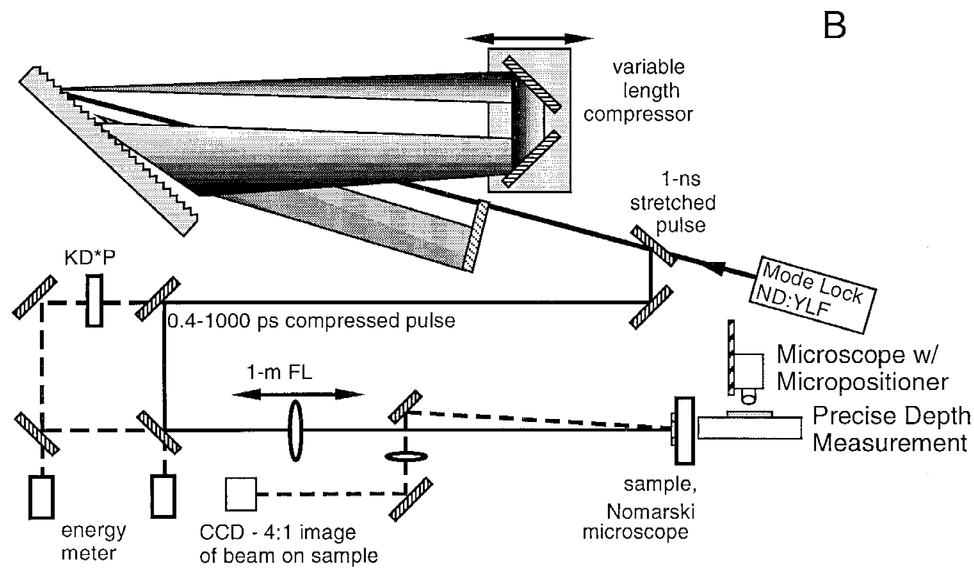


Fig. 1. Experimental setup: **(A)** ablation efficiency and AR measurements for the XeCl, Er:YAG and Ho:YSGG lasers, **(B)** setup and sample holder for the CPA system.

tain a spot area of 1 mm^2 for each laser except for the CPA with a 0.5 mm beam diameter. Energy was monitored following each irradiation by removing the nail and exposing an energy meter (Gentec model PRJ-M, ED 500 head) to the beam. Lasers were studied at a pulse repetition rate (PRR) of 4 Hz in all cases except for the CPA, which was operated at 10 Hz. Five ablation sites were made with each laser parameter setting.

Ablation rates for the Er:YAG, Ho:YSGG, and the XeC1 lasers were determined by placing the energy meter behind the nail, away from the laser beam. Ablation was considered complete when light energy registered on the meter indicating perforation. The AR was calculated by taking the ratio of the measured nail thickness to the number of pulses needed to perforate the nail plate. The quoted AR, in a strict sense, therefore, represents the mean ablation rate averaged over the entire nail thickness. Actual AR are expected to slightly vary as the ablation crater size increase.

Ablation rates for the CPA were determined by viewing the crater's edge and floor with an optical microscope coupled to a calibrated micropositioning digital gauge (Digital gauge DG-2100S, Sony, Japan) after 100 pulses. The microscope objective was focused on the upper edge of the crater

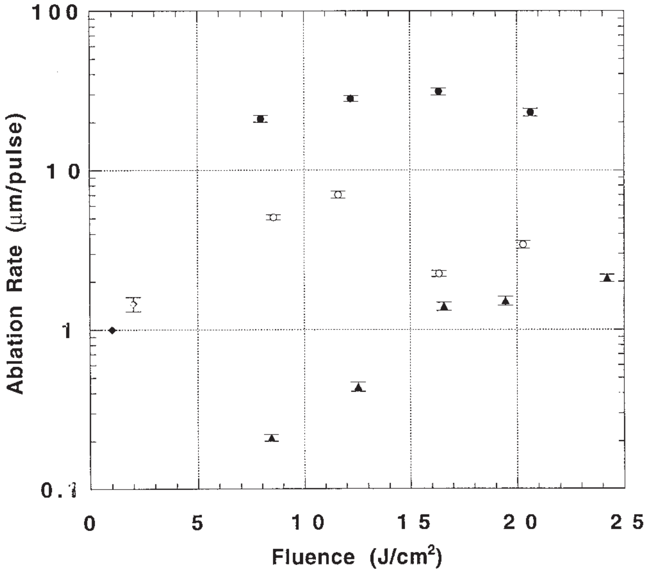


Fig. 2. Ablation rate as a function of fluence—Ho:YSGG (triangles), XeCl (hollow circles), Er:YAG (full circles), and CPA (diamonds at 1 and 2 mJ).

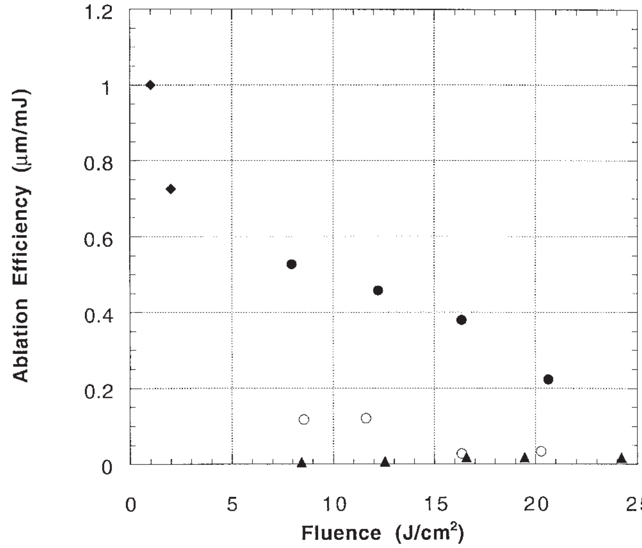


Fig. 3. Ablation efficiency comparison in Ho:YSGG (triangles), XeCl (hollow circles), Er:YAG (full circles), and CPA (diamonds at 1 and 2 mJ).

and then refocused on the crater floor. The depth gauge measured the vertical motion of the objective to within 0.01 μm (Fig. 1). Ablation rates (AR) were recorded as micrometer per pulse. The means and standard deviations were calculated from each set of ablation craters corresponding to each laser parameter combination. Ablation efficiency (AE) was defined as the depth of ablation (measured in μm) produced by 1 mJ of energy and calculated from the AR by dividing AR per pulse values by the energy per pulse.

Post ablative surface characteristics (degree of charring, cracking or other surface deformations) were evaluated using light microscopy (SZH-ILLD Olympus Optical Co, Japan) at a magnification of 60X and using scanning electron microscopy (SEM). Following irradiation, nails were washed with 100% EtOH, mounted on stubs using colloidal silver liquid (Ted Pella, Redding, CA.), and gold-coated on a PAC-1 Pelco advanced coater 9500 (Ted Pella). Micrographs were taken on a Philips 515 (Mohawk, NJ) SEM.

RESULTS

Ablation Rates

AR data from all four laser systems are summarized in Figure 2. Ablation with the Ho:YSGG laser shows a clear dependence of the AR on fluence. A significant increase in AR is observed between 8 and 17 J/cm^2. At 17 J/cm^2, the AR increases from <0.5 μm/pulse to 1.4 μm/pulse. AR then increases up to >2 μm/pulse at 24 J/cm^2.

XeC1 ablation is higher at lower fluences (10–15 J/cm^2) than those of the Ho:YSGG. At 5 and 7 μm/pulse, however, it is considerably lower than that of the Er:YAG. There is actually a drop in AR at higher energies, which probably can be explained in terms of increased plasma shielding. Given that enhanced plasma generation also results in more significant mechanical transients, it appears that avoiding pulse energies >15–18 J/cm^2 is advisable.

The highest AR were observed with Er:YAG. Here, the strong absorption of 2.94 μm radiation results in consistently high AR, which increases linearly from 20 μm/pulse at 10 J/cm^2 to >30 μm/pulse at 20 J/cm^2. The sudden decrease in AR as pulse fluence increases to 25 J/cm^2/pulse is not completely understood. Such an observation, however, could be related to increased plasma density, which shields the surface from most of the pulse energy [9].

Finally, AR with the CPA was studied only at 3 mJ/p (3 J/cm^2). Consistent ARs of ~ 1.0 μm/pulse at 3 mJ pulse energy were observed.

Figure 3 compares the AEs of the four lasers. With the CPA system, AEs of ~ 1 μm per mJ at 1 mJ/pulse was consistently observed and is higher than all other lasers studied. For comparison, Ho:YSGG is the poorest ablator with AEs lower than 0.05 μm/mJ. XeCl is somewhat more efficient with ~ 0.1 μm/mJ at 10 J/cm^2 to ~ 0.03 μm/

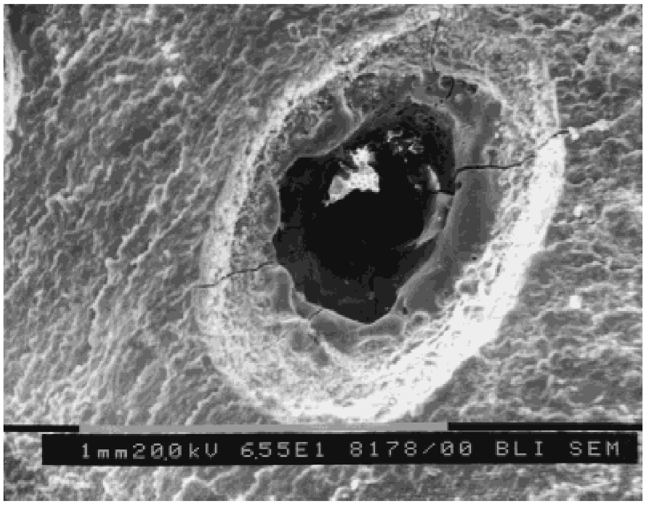


Fig. 4. SEM of Ho:YSGG laser-generated crater in nail bed.

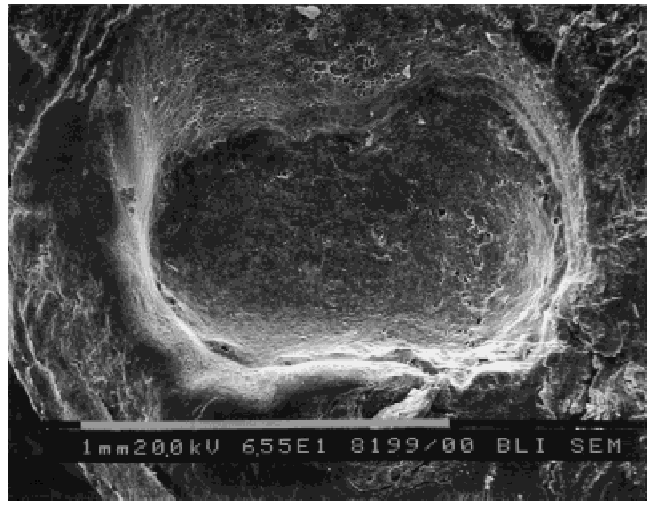


Fig. 5. SEM of Er:YAG laser-generated crater in nail bed.

mJ at 25 J/cm². Er:YAG is the closest ablator to the CPA with AEs > 0.5 μm/mJ at 10 J/cm², which then fall near 0.2 μm/mJ at 25 J/cm². Perhaps the most interesting fact evident from Figure 3, however, is the observation that these high AEs for the CPA are obtained at the very low fluence of 1 J/cm². This must be contrasted with the highest AE obtained with the Er:YAG or XeCl at 40 times that energy level.

SEM Studies

Ho:YSGG. Ablation resulted in an oval shaped crater ~ 1 mm in length (Fig. 4). The crater, conical in shape, drops to smaller dimensions toward the floor. Walls appeared jagged, partially cracked (cracks are several microns wide and transverse the entire crater), and covered with melted and resolidified tissue. Cracking formed during or after the resolidification process.

XeCl. Rectangular ablation craters were formed roughly 1 mm² in size (Fig. 5). No cracking or melting were observed. Crater walls appear almost vertical.

Er:YAG. Ablation craters were rectangular in shape ~ 1.0 × 0.8 mm in size (Fig. 6). Wall and crater floor surfaces are clean with no evidence of melting. In deep craters, few but large cracks were observed. No cracking was observed in shallower craters.

CPA. Figure 7 shows the SEM resulting from CPA ablation. Craters correspond closely to the beam shape, are circular, and ~ 0.45 mm in diameter. Walls were very smooth with no evidence of cracking or melting.

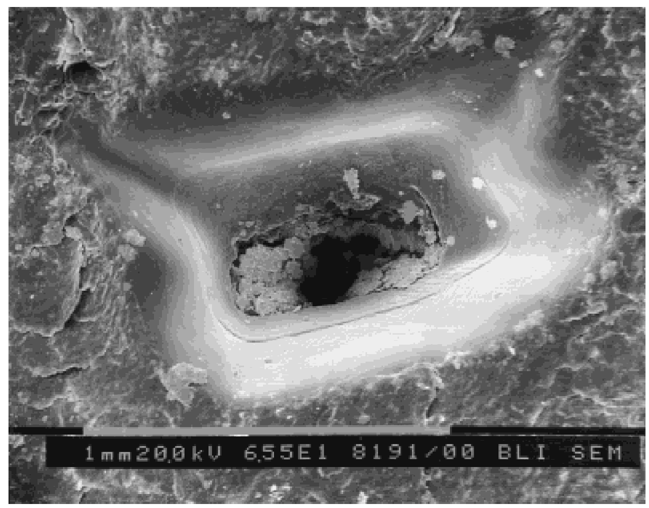


Fig. 6. SEM of XeCl laser-generated crater in nail bed.

DISCUSSION

Due to differences in their interaction with tissue, laser ablation of nail plates by short and long pulses can clearly be distinguished. Briefly, longer pulse (>10 ps) interactions with hard tissue are dominated by the absorption characteristics of the light [8]. Laser radiation, absorbed in a layer near the surface, heats up and melts the material. Removal, however, is not the only a consequence of direct vaporization. Vaporization also creates the recoil momentum, which then pushes out the liquid material by secondary ejection. When laser intensity is increased further, plasma formation takes place near the surface. Plasma formation shields the material and ablation efficiency drops. Long pulse heating is sufficiently

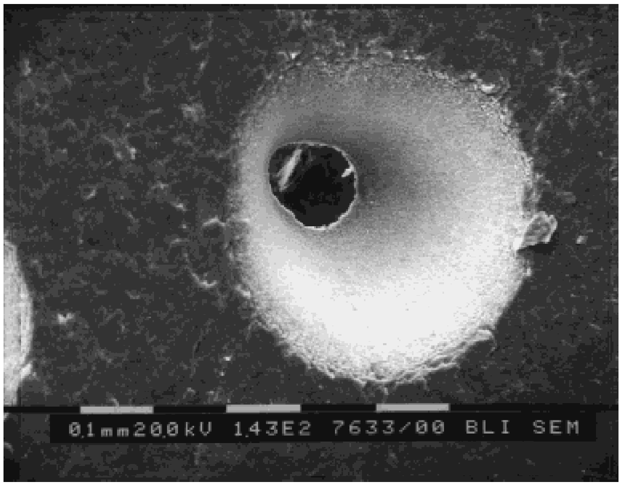


Fig. 7. SEM of 350 fs CPA laser-generated crater in nail bed.

slow to allow thermal energy to penetrate deep enough into the material to induce both direct damage and thermo-mechanical stresses, which generate cracks in the material. As a result, collateral damage is often unacceptably high for various medical applications. Shortening the pulse yields smaller volume heating and decreases the threshold energy needed for ablation.

The Er:YAG, Ho:YSGG, and XeCl excimer lasers fall into the long pulse category and were selected based on their absorption characteristics. The wavelength emission of these lasers is highly absorbed by water and protein. It is also important to note the pulse duration and structure of these longer pulse lasers. The XeCl laser emits pulses of 15 ns duration, whereas the Er:YAG and Ho:YSGG lasers emit 250 μs macropulses (at 4 Hz) containing a train of 1 μs pulses separated by ~10 μs.

Other than the CPA laser, the highly absorbed Er:YAG radiation was the most efficient ablator. However, high absorption of 25 micropulses at 100 MHz resulted in sufficient thermal build up to generate thermoelastic stresses, which were manifested in some samples by tissue cracking. The Ho:YSGG extinction length is about two orders of magnitude larger than the Er:YAG and thus effects a much larger volume of tissue. Instead of the rapid vaporization, which results in cooler ablation (as in the Er:YAG), thermal buildup produces melting and cracking of the tissue.

The XeCl system, another laser with relatively deep penetration, has shown very interesting results in that its ablation rates were significantly higher than those of the Ho:YSGG and essentially free of stress or mechanical damage. Clearly, the short 15 ns pulses allow sufficiently localized deposition of energy to result in explosive ejection of material, which removes the heat, relieves the stress, and avoids the cracking or charring seen with Er:YAG/Ho:YSGG lasers.

Although the CPA system was clearly the poorest per-pulse ablator, in many respects, the system was the most promising. Small craters (300–400 μm) were easily produced with no evidence of cracking or thermal damage. Craters were reproducible and consistent in size and appearance. AE of 1 μm/mJ at 1 J/cm^2 was consistent and is actually more efficient in terms of crater depth etched per pulse than all other lasers studied. For comparison, Ho:YSGG is the poorest ablator with AE ranging from ~0.005 μm/mJ at 8 J/cm^2 to ~0.012 μm/mJ at 24 J/cm^2. XeCl is somewhat more efficient with ~0.1 μm/mJ at 8 J/cm^2 to 0.04 μm/mJ at 25 J/cm^2 mJ/pulse. Er:YAG is the closest most efficient ablator to the CPA with 0.5 μm/mJ at 10 J/cm^2 and down to 0.3 μm/mJ at 25 J/cm^2. Also of interest is the fact that the AE appeared to drop with fluence in the case of Er:YAG while increasing with fluence using the XeCl and Ho:YSGG lasers. This effect was observed by Walsh et al. [11] in Er:YAG ablation of bone. They speculated that this effect is due to plasma shielding, which also was a reasonable explanation for the present observations in nail tissue.

CONCLUSIONS

We have investigated the interaction characteristics of an ultrashort laser pulse train with the hard tissue of the nail plate. Negligible collateral damage and highly efficient ablation rates were demonstrated with the CPA followed by the mid-IR Er:YAG and the near-UV XeCl excimer lasers. Very poor ablation efficiencies were observed with the Ho:YSGG. However, although ablation with all other systems is noisy and associated with a significant plasma spark and snapping sound, ablation with the CPA is accomplished with significantly reduced energy per pulse and virtually free of mechanical or acoustical impact. Of the four lasers tested, three clearly show the potential for achieving the goal of nail plate perforation in order to facilitate topical drug delivery for treatment of subsurface nail pathology. In particular, the CPA stands out as a significantly superior tool for its precise, highly efficient operation, which minimizes collateral damage. Although additional studies are required to determine the in

situ biological effects of laser ablation and resultant barrier renewal kinetics, the potential advantages of the proposed removal of nail substrate in the clinical management of patients with onychomycosis and psoriasis are convincing: (1) increased penetration of topically applied drugs through the plate into the bed without removing the nail, (2) eliminates the need for systemic treatment and associated side effects, and (3) allows patients with only one or two diseased nails to receive treatment without having to use systemic medications for their limited involvement.

ACKNOWLEDGMENTS

This work was supported by NIH grant ≠5P41RR01192, Department of the Navy grant ≠N00014-90-0-0029, and Department of the Energy Grant ≠DE-FG0391ER61227. This research was performed under the auspices of the U.S. Department of Energy, the Lawrence Livermore National Laboratory under Contract No. W-7405-ENG-48. J. S. N.'s contribution was supported by NIH grants ≠IR29-AR41638-O1A1 and IR01AR42437-O1A1.

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